AFRL-AFOSR-UK-TR-2011-0063

# Towards Graphene-Based Electronics

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EOARD GRANT 08-3088

Report Date: January 2012

Final Report for 24 July 2008 to 24 July 2011

**Distribution Statement A: Approved for public release distribution is unlimited.**

**Air Force Research Laboratory**
**Air Force Office of Scientific Research**
**European Office of Aerospace Research and Development**
**Unit 4515 Box 14, APO AE 09421**

# REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188



**1. REPORT DATE *(DD-MM-YYYY)***
28-01-2012

**2. REPORT TYPE**
Final Report

**3. DATES COVERED *(From – To)***
24 July 2008 – 24 July 2011

**4. TITLE AND SUBTITLE**

**Towards Graphene-Based Electronics**

**5a. CONTRACT NUMBER**
FA8655-08-1-3088

**5b. GRANT NUMBER**
Grant 08-3088

**5c. PROGRAM ELEMENT NUMBER**
**61102F**

**6. AUTHOR(S)**

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**5d. PROJECT NUMBER**

**5d. TASK NUMBER**

**5e. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
University of Manchester
Oxford Road
Manchester, United Kingdom M13 9PL

**8. PERFORMING ORGANIZATION REPORT NUMBER**
N/A

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

EOARD
Unit 4515 BOX 14
APO AE 09421

**10. SPONSOR/MONITOR'S ACRONYM(S)**
AFRL/AFOSR/RSW (EOARD)

**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**
**AFRL-AFOSR-UK-TR-2011-0063**

**12. DISTRIBUTION/AVAILABILITY STATEMENT**

Approved for public release; distribution is unlimited.

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT** During the last year, we have published more than 20 research papers including 2 *Science* papers, 4 papers in *Nature Physics* and *Nature Communications* and 5 *Phys. Rev. Letters*. The most important technological result probably was the development of fabrication procedures to encapsulate graphene between boron-nitride crystals, which allows us to routinely achieve mobilities above 100,000 cm2/Vs and demonstrate room-temperature ballistic transport at micron scale (*Nano Lett.* **11**, 2396, 2011). This development also led to the first double-layer graphene heterostructures, in which we reported interesting interaction phenomena (*Nature Phys.* online 2011) and which continue to be in the focus of our attention offering a wealth of new physics and potential applications. Interaction phenomena have also been studied in suspended devices made from graphene and its bilayer (*Science* **333**, 860, 2011; *Nature Phys*. **7**, 701, 2011) and by using the nonlocal geometry (*Science* **332**, 328, 2011). As a result we can now routinely make and investigate complex graphene-BN heterostructures with mobilities 10 times higher than for graphene on the standard Si substrates. For suspended graphene devices, we achieve mobilities well above a million, that is, 100 times higher than for graphene on a Si substrate. Another important development over the last year was the demonstration of a graphene-based derivative, fluorographene that is a two-dimensional version of Teflon (*Small* **6**, 2877, 2010). In all these publications, the PIs have gratefully acknowledged the AFOSR support. As concerns the entire 3-year project, it resulted in 4 *Science* research papers and dozens of reports in *Nature* series magazines, *Phys. Rev. Letters, Nano Letters* and other high-quality research journals. Despite the short reported period, our research has already caused very high impact that can be quantified by the number of citations for the papers supported by the AFOSR grant. Two of them (*Science* 2009 and *Rev. Mod. Phys.* 2009) were cited >1,000 times, and another *Science* 2009 is rapidly approaching this threshold. Four other papers have already attracted more than 100 citations, and we are confident that no less than 20 research publications supported by this grant will eventually attract more than 100 citations. Our results were also presented in more than 100 invited talks, including approximately 20 named and plenary lectures. We were awarded the 2010 Nobel Prize in Physics, the 2010 Carty Award from the US National Academy of Sciences, and the 2009 Körber Prize,

**15. SUBJECT TERMS**

EOARD, Electronic Devices, Electronic Materials, graphene

| 16. SECURITY CLASSIFICATION OF: a. REPORT | b. ABSTRACT | c. THIS PAGE | 17. LIMITATION OF ABSTRACT | 18, NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| UNCLAS | UNCLAS | UNCLAS | SAR | 6 | SCOTT DUDLEY, Lt Col, USAF |
| | | | | | **19b. TELEPHONE NUMBER** *(Include area code)* +44 (0)1895 616162 |

**Standard Form 298** (Rev. 8/98)
Prescribed by ANSI Std. Z39-18

FINAL REPORT

***Towards Graphene-Based Electronics***

**Grant FA8655-08-1-3088**

Principal Investigators: *Professors Andre Geim* and *Kostya Novoselov*

The AFOSR BAA grant notably contributed to the rapid progress achieved in graphene research over the last 3 years and was essential in helping the PIs to keep ahead of ever increasing competition. Before summarizing the overall progress, let us describe the latest developments over the final year of Oct 2010 – Sept 2011 (details for previous years can be found in the corresponding annual reports).

During the last year, we have published more than 20 research papers including 2 *Science* papers, 4 papers in *Nature Physics* and *Nature Communications* and 5 *Phys. Rev. Letters*. The most important technological result probably was the development of fabrication procedures to encapsulate graphene between boron-nitride crystals, which allows us to routinely achieve mobilities above 100,000 $cm^2/Vs$ and demonstrate room-temperature ballistic transport at micron scale (*Nano Lett.* **11**, 2396, 2011). This development also led to the first double-layer graphene heterostructures, in which we reported interesting interaction phenomena (*Nature Phys.* online 2011) and which continue to be in the focus of our attention offering a wealth of new physics and potential applications. Interaction phenomena have also been studied in suspended devices made from graphene and its bilayer (*Science* **333**, 860, 2011; *Nature Phys*. **7**, 701, 2011) and by using the nonlocal geometry (*Science* **332**, 328, 2011). As a result we can now routinely make and investigate complex graphene-BN heterostructures with mobilities 10 times higher than for graphene on the standard Si substrates. For suspended graphene devices, we achieve mobilities well above a million, that is, 100 times higher than for graphene on a Si substrate. These recent developments are essential for improving the performance of graphene-based transistors and extending their frequency range. In addition, the high-quality heterostructures offer a possibility to proceed along several new venues towards graphene-based electronics such as, for example, vertical field-effect tunnelling transistors. Another important development over the last year was the demonstration of a graphene-based derivative, fluorographene that is a two-dimensional version of Teflon (*Small* **6**, 2877, 2010). In all these publications, the PIs have gratefully acknowledged the AFOSR support.

As concerns the entire 3-year project, it resulted in 4 *Science* research papers and dozens of reports in *Nature* series magazines, *Phys. Rev. Letters, Nano Letters* and other high-quality research journals. Despite the short reported period, our research has already caused very high impact that can be quantified by the number of citations for the papers supported by the AFOSR grant. Two of them (*Science* 2009 and *Rev. Mod. Phys.* 2009) were cited >1,000 times, and another *Science* 2009 is rapidly approaching this threshold. Four other papers have already attracted more than 100 citations, and we are confident that no less than 20 research publications supported by this grant will eventually attract more than 100 citations.

Our results were also presented in more than 100 invited talks, including approximately 20 named and plenary lectures. We were awarded the 2010 Nobel Prize in Physics, the 2010 Carty Award from the US National Academy of Sciences, the 2009 Körber Prize, several other prestigious international prizes as well as many distinctions such honorary fellowships and doctorates.

LIST OF PUBLICATIONS FOR THE FINAL YEAR (Oct 2010 – Sep 2011)


1. D. C. Elias, R. V. Gorbachev, A. S. Mayorov, S. V. Morozov, A. A. Zhukov, P. Blake, L. A. Ponomarenko, I. V. Grigorieva, K. S. Novoselov, F. Guinea, *A. K. Geim*. Dirac cones reshaped by interaction effects in suspended graphene. *Nature Phys.* **7**, 701-704 (2011).
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10. F. Carbone, G. Aubock, A. Cannizzo, F. van Mourik, R. R. Nair, *A. K. Geim*, K. S. Novoselov, M. Chergui. Femtosecond carrier dynamics in bulk graphite and graphene paper. *Chem. Phys. Lett.* **504**, 37-40 (2011).
11. R. V. Gorbachev, I. Riaz, R. R. Nair, R. Jalil, L. Britnell, B. D. Belle, E. W. Hill, K. S. Novoselov, K. Watanabe, T. Taniguchi, *A. K. Geim*, P. Blake. Hunting for monolayer boron nitride: optical and Raman signatures. *Small* **7**, 465-468 (2011).
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16. R. R. Nair, P. Blake, J. R. Blake, R. Zan, S. Anissimova, U. Bangert, A. P. Golovanov, S. V. Morozov, *A. K. Geim*, K. S. Novoselov, T. Latychevskaia. Graphene as a transparent conductive support for studying biological molecules by transmission electron microscopy. *Appl. Phys. Lett.* **97**, 153102 (2010).
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# ANNUAL REPORT 2010

## *Towards Graphene-Based Electronics*

## Grant FA8655-08-1-3088

Principal Investigators: *Professors Andre Geim* and *Kostya Novoselov*

The AFOSR BAA grant has significantly helped PIs in investigation of fundamental properties of graphene and its possible applications in electronics beyond the Si age, including the possibility of graphene-based ballistic transistors. Over the reported period of Oct 2009 – Sept 2010, the Manchester team has made significant progress in the understanding of the properties of graphene.

The most notable result has been the demonstration that by using strain it is possible to open significant band gaps and even achieve the quantum Hall effect without magnetic field (*Nature Phys.* 2010). Within a few months, this effect was confirmed experimentally by a Stanford group who reported pseudomagnetic fields up to 400 T and energy gaps > 0.5eV. In another set of work, PIs have demonstrated that so called resonant scatterers could be responsible for limiting carrier mobility in graphene (*Nano Lett.* 2010). This works continues, and we can now achieve mobilities over 100,000 $cm^2/Vs$ for graphene encapsulated within boron-nitride. In such devices room-temperature mean free path reaches over 1 $\mu$m (unpublished). PIs has also measured quantum capacitance of graphene and demonstrated new devices with variable capacitance (Ponomarenko *et al*, *PRL* 2010). Measurements of graphene's magnetization revealed that graphene is diamagnetic and no sign of ferromagnetism was observed down to liquid helium temperatures, contrary to many artefacts reported in literature (Sepioni *et al*, *PRL* 2010).

Over the reported period, PIs have published 10 papers listed below, which acknowledged the AFOSR support. Our results were also presented in more than 40 invited talks, including 10 named and plenary lectures. In 2010, we were awarded the Nobel Prize in Physics and J. J. Carty Award from the US National Academy of Sciences.


1. F. Guinea, M. I. Katsnelson, *A. K. Geim*. Energy gaps and a zero-field quantum Hall effect in graphene by strain engineering. *Nature Phys.* **6**, 30-33 (2010).
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10. E. V. Kurganova, A. J. M. Giesbers, R. V. Gorbachev, *A. K. Geim*, K. S. Novoselov, J. C. Maan, U. Zeitler. Quantum Hall activation gaps in bilayer graphene. *Solid State Commun.* **150**, 2209-2211 (2010).

# REPORT

## *Towards Graphene-Based Electronics*

### Grant FA8655-08-1-3088

Principal Investigators: *Professor Andre Geim* and *Dr Kostya Novoselov*

The AFOSR BAA grant has significantly helped PIs in investigation of fundamental properties of graphene and its possible applications in electronics beyond the Si age, including the possibility of graphene-based ballistic transistors.

Over the reported period of Oct 2008 – Sept 2009, the Manchester team has made significant progress in the understanding of the properties of graphene. By using graphene immersed in high-k dielectrics, PIs have demonstrated that charged impurities can be contributing scatterers but do NOT limit graphene's mobility to currently achievable values of less than 20,000 $cm^2/Vs$ for graphene on a substrate (published in *Phys. Rev. Lett* 2009). The scattering mechanism has been investigated in several publications of PIs and, also, other groups addressed this problem but no clear picture has emerged yet.

Furthermore, PIs' team has investigated roughness of graphene membranes and demonstrated that nanoscale roughness is intrinsic, even if no adsorbates are present (*Nature Nanotechnology* 2008).

The most significant achievement over this period was the creation of graphane, a chemical derivative of graphene with one hydrogen atom attached to each carbon site (*Science* 2009). This new material is an insulator, which shows that the hydrogenation could be used to locally create semiconducting and insulating regions in all-graphene circuits. More generally, the work has demonstrated numerous opportunities that chemistry potentially offers for graphene research.

In 2009, PIs have published two reviews on graphene, in *Rev. Mod. Phys.* and in *Science*. Our results were also presented in more than 20 invited talks, including 5 named and plenary lectures.

Over the reported period, our work was acknowledged by the European Körber Prize, "Einstein Professorship" of the Chinese Academy of Sciences, and honorary doctorate from the Delft University (Netherlands).

PUBLICATIONS SUPPORTED BY THE AFOSR GRANT


1. P. Blake, R. Yang, S. V. Morozov, F. Schedin, L. A. Ponomarenko, A. A. Zhukov, I. V. Grigorieva, K. S. Novoselov, A. K. Geim. Influence of metal contacts and charge inhomogeneity on transport properties of graphene near the neutrality point. *Solid State Commun.* **149**, 1068-1071 (2009).
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